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MECHANICS

OF

VENTILATION.

BY

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PREFACE.

THE Mechanics of Ventilation was prepared in the intervals of professional work, and is, like the generality of engineering papers, by no means perfect from the literary point of view. Indeed, in dealing with "actualities" it may be an open question whether literary polish is at all necessary. It frequently happens that the highly polished paper contains very little information, an unfortunate predicament into which the author hopes he has not fallen.

It is intended to extend this theory of ventilation to mines. A lack of definite data presents such extensions at present.

G. W. R.

ROCHESTER, Nov. 1, 1877.

THE MECHANICS OF VENTILATION.

FIRST PRINCIPLES.

THE necessity for change of air in inhabited spaces is rendered evident by considering the sources of contamination : they are,

a. The production of carbonic acid by respiration.

b. Increase of moisture from the same cause and exhalation from the body.

c. Organic impurities from the bodily exhalations.

d. Heat thrown off from the occupants and from the lights at night; and

e. The production of carbonic acid from the lights.

The object of ventilation, therefore, is to remove foul air and substitute fresh air in place of the foul air so removed.

Ventilation, then, reduced to its simplest terms, is a matter merely of the movement of bodies of air; and, since, air is a substance possessing weight, the whole question is one of mechanics, and is in the fullest sense susceptible of numerical computation.

This being granted further progress is comparatively rapid, consisting (1) of the development of the laws of air in motion, and (2) in the application of those laws to the removal of foul air, and the consequent supplying of fresh air in buildings and closed structures generally.

Before entering upon the strictly mechanical portion of the subject, it will be well to consider briefly (1) the nature and extent of the contamination rendering change of air in inhabited confined spaces necessary, and (2) the collateral head of ventilation—warming.

SOURCES OF CONTAMINATON.

a. Production of carbonic acid by respiration. When air passes into the

lungs it undergoes a chemical change whereby a certain amount of carbonic acid is produced. This when expired adds to the impurity of the air, and were its production by respiration continued a sufficient time in any tight space, the air would ultimately become so impure as to produce death. It has been found by experiment that air in its normal condition contains in all parts of the world an amount of carbonic acid equal to from three to four volumes in 10,000. That some must exist in the air will be readily inferred by considering that respiration and combustion always produce this gas. The amount, however, was only determined by the researches of Regnault, who analyzed air from many localities. When carbonic acid is the only impurity from eight to ten volumes in 10,000 may be respired without serious inconvenience, though six volumes in 10,000 is taken as the limit of good ventilation for reasons to appear hereafter. An adult produces 0.6 of a cubic foot of carbonic acid per hour.

b. Increase of moisture from respiration and bodily exhalations. The amount of moisture present in the air at different times varies greatly. Observation shows that there are certain amounts of moisture which when exceeded lead to a rapid deterioration of the air. From 4.5 to 5.0 grains in a cubic foot of air at 60°–62° is the limit of good ventilation.

c. Organic impurities from the bodily exhalations. There is always present in illy-ventilated apartments, especially school-rooms where children from the poorer classes are present, a certain unpleasant smell which a medical friend of large experience in ventilation characterises as "cheesy." In simple justice it must be said that this smell is by no means confined to school-rooms of the kind indicated. Excellent examples of it are frequently noticed in concert halls, theatres, lyceums, and in private houses where even an intimation of uncleanliness would be rank injustice. Organic analysis has thus far been unable to do more than detect the simple presence of

this ill-smelling enemy of the human race. It has been found, however, that a rapid increase of the organic impurity takes place when carbonic acid exceeds six volumes in 10,000, or when moisture rises above five grains in a cubic foot of air at 60°–62°. The reason for the limit of carbonic acid and moisture as above given is therefore apparent.

d. Heat thrown off from occupants and from the lights at night. It has been determined by observation that an adult gives out 470–490 units of heat per hour, and that an ordinary sperm or tallow candle gives out in burning one hour substantially the same amount. The specific heat of air is 0.238 when water is taken as unity, consequently the heat from a single person or single candle in one hour would raise 1974 lbs. of air 1°, or, since, a pound of air at 60°–62° equals thirteen cubic feet (exactly 13.09 at 60°) we have heat enough to raise 25662 cubic feet 1°. It will be shown, hereafter, that 2000 cubic feet of air per hour is a fair allowance for an adult.

It follows that every person, and every candle, gives out heat enough in an hour, to raise the supply per hour, for each person, from 12° to 13°. If a room were constructed of a capacity equal to say ten persons, and the air supply exactly regulated to give each 2000 cubic feet per hour, the bodily heat alone would increase the temperature of the supply from 12° to 13°.

A large majority of buildings are now lighted by coal gas; we will, therefore, consider the amount of heat produced by the combustion of a cubic foot, having ascertained which it will of course be easy to calculate the elements for rooms of any given capacity and number of lights.

The average of a large number of analyses of coal gas of from twelve to eighteen candle power is as follows :

Hydrogen	=	43.76
Marsh Gas	=	40.47
Carbonic Oxide	=	5.94
Olefiant Gas	=	6.58
Nitrogen	=	1.05
Oxygen	=	0.47
Carbonic Acid	=	0.75
Aqueous Vapor	=	1.00
		100.02

The specific gravity of sixteen candle power gas is approximately 0.450, common air at a temperature of 60° being unity. A pound of air at 60° contains exactly 13.09 cubic feet; consequently, a pound of coal gas of a specific gravity 0.450 and at the same temperature contains:

$$\frac{13.09}{0.450} = 29.09 \text{ cubic feet.}$$

A cubic foot of such gas therefore weighs

$$\frac{1.00000}{29.09} = 0.0343 \text{ lbs.}$$

Taking the percentage of the constituents of coal gas as given above, we have

the following for the weight in pounds of each in a cubic foot of gas:

Hydrogen	=	0.01501
Marsh Gas	=	0.01388
Carbonic Oxide	=	0.00203
Olefiant Gas	=	0.00225
Nitrogen	=	0.00036
Oxygen	=	0.00016
Carbonic Acid	=	0.00025
Aqueous Vapor	=	0.00034
		0.03428

Multiplying each of these weights by the caloric modulus for the corresponding element and we have the number of heat-units evolved in the combustion of that element, and the sum of these units will be the theoretical heat obtained by the combustion of a cubic foot of gas. The calculation referred to the Fahrenheit scale will stand as follows:

Hydrogen	$=34462\times0.01501\times1.8$	$=931.09$
Marsh Gas	$=13063\times0.01388\times1.8$	$=326.36$
Carbonic Oxide	$=3403\times0.00203\times1.8$	$=12.42$
Olefiant Gas	$=11857\times0.00225\times1.8$	$=48.00$
		1317.87 heat units.

The remaining constituents are non-combustible.

The caloric moduli for the different gases as here used were obtained by combustion in an atmosphere of pure oxygen, while combustion in practice will, of course, take place in common air. Comparing this calculated amount of heat with the observed amount, obtained by calorimetrical tests of illuminating gas of the candle power, and specific gravity above given, shows that a reduction of the calculated heat of forty per cent. is necessary to make calculation agree with experiment. This reduction is undoubtedly owing, largely, to imperfect combustion, in addition to difference of condition. Making such reduction we have

$1317.85 \times 0.6 = 790.7 =$ approximate number of heat-units from the combustion of one cubic foot of sixteen candle power illuminating gas.

The mean of several tests was 705 heat-units per cubic foot of gas. We will take, for purposes of calculation, 750 heat-units per cubic foot of gas.

Gas burners range from three to six cubic feet consumption per hour, and, where no special arrangements are made for removing the heat and products of combustion from the burners, a simple calculation will show the great influence upon the health of the occupants of an apartment exerted by this apparently insignificant source of contamination.

e. The production of carbonic acid from the lights. According to many careful experiments the carbonic acid from a sperm or paraffine candle equals 0.31 of a cubic foot per hour. Calculation based upon the average composition of coal gas shows that the combustion of a cubic foot of gas produces 0.43 of a cubic foot of carbonic acid. Such a calculation stands substantially as follows: Taking the average analysis of coal gas given above, we have by calculation from chemical equivalency the weight of carbon in a cubic foot of gas, and from this we derive the weight of oxygen necessary to convert that amount of carbon into carbonic acid. The weight of

the carbon, plus the weight of the oxygen equals the weight of carbonic acid produced, and is found to be 343 grains. Density of carbonic acid gas is 1.5 at a temperature of 60°. A cubic foot weighs at that temperature then 801 grains, a cubic foot of air weighing 534 grains at that temperature. Dividing the weight of a cubic foot of carbonic acid by the weight of that gas from a cubic foot of coal gas, and we have 0.43 of a cubic foot as the amount of carbonic acid produced by the combustion of a cubic foot of coal gas.

It is evident then that a considerable amount of oxygen is required for the various processes of respiration and combustion going on in confined spaces, and that a further deterioration of the air is continually taking place by reason of the presence of the nitrogen previously mixed with the oxygen so removed; that is to say, oxygen the life-supporting agent in these various processes is continually being removed, while nitrogen the inert, useless element is left behind.

Air in its normal condition contains twenty-three per cent. by weight of oxygen, and seventy-seven per cent. of nitrogen. It will soon result, however, in any confined space where respiration and combustion are going on, that the amount of oxygen constantly decreases while the nitrogen and carbonic acid increase relatively to the amount of oxygen present.

A farther source of contamination is found in insufficient sewer connections, though this part of the subject has been so often discussed that it is unnecessary to consider it at length here.

WARMING.

According to General Morin's paper on warming and ventilation, a translation of which appears in the annual reports of the Smithsonian Institution for 1873–74, heating apparatus should be considered in three different respects:

1. In regard to economy of fuel.
2. In regard to effect on health.
3. In regard to comfort.

The nature of the service to be performed should always be considered in deciding upon the apparatus for fulfilling these considerations. For instance, where occupancy is at intervals, and then only for a short time, the first will decide the choice of method. In buildings occupied more or less continuously, the second consideration should have more weight, while in dwelling houses the second and third together should influence the choice.

The cheapest method of heating is by stoves, more than ninety per cent. of the heat being realized in this way. The first cost is also much less than by the other methods.

Comfortable and healthful heating is obtained by open fire-places, two types of which may be distinguished :

1. Ordinary fire-places.
2. Ventilating fire-places.

The ordinary fire-place takes its supply of air directly from the room and heats solely by radiation. Its heating

effect does not exceed fourteen per cent. of the total amount of heat produced. It is healthful and comfortable but not at all economical.

Captain Galton, of the British army, invented a form of the ventilating fire-place which furnishes a very satisfactory solution of the problem of pleasant, healthful heating, combined with excellent ventilation. It consists of a grate with a flue leading therefrom as in the ordinary arrangement. The flue, however, is of a good conducting and radiating material, and passes up through an exterior flue, into which air is admitted from the outside at the back of the grate. This air is warmed by coming in contact with the interior flue, which gives it an upward tendency, and is withdrawn near the ceiling into the room in which the fire-place is located, or it may be conducted into the rooms of the second story. The air to support combustion is taken from the room warmed as in the previous plan. The heating effect realized by this method is thirty-five per

cent. of the total heating power of the fuel.

Heating by steam or hot water is pleasant, and when in connection with proper ventilation exceedingly healthful. The heating effect realized is nearly ninety per cent.

Hot air, when properly regulated, is pleasant, and in connection with ventilation, healthful. Heating effect seventy-five per cent.

MECHANICS OF AIR.

At a temperature of 60°, 13.09 cubic feet of air weigh exactly one pound. A cubic foot at the same temperature weighs 534 grains. As already remarked, air in common with all other ponderable bodies obeys the law of gravitation, and, because of the slight attraction between its particles, it is, like gases generally, extremely sensitive to changes of temperature or pressure.

According to Gay Lussac's law the volume of one and the same gas varies with the temperature.

With notation as follows :

V_0 = volume at 32° and barometer at twenty-nine and ninety-two hundredths inches.

V = volume at the temperature t.

$a = 0.00204$ = coefficient of expansion, expresses the increase of volume for an increase in temperature of one degree Fahrenheit.

We have by formula

$$V = [1 + a(t-32)]V_0$$
$$= [1 + 0.00204(t-32)]V_0 \quad (1)$$

In case the air is farther heated to the temperature t_1 the corresponding volume becomes

$$V_1 = [1 + 0.00204(t_1-32)]V_0 \quad (2)$$

the ratio of the volumes V and V_1 will be

$$\frac{V}{V_1} = \frac{1 + 0.00204\,(t-32)}{1 + 0.00204(t_1-32)}. \quad (3)$$

According to Mariotte's law we have :

1. The density of one and the same quantity of air is proportional to its pressure.

2. The volumes of one and the same quantity of air are inversely as the pressures.

3. From 1 and 2 it follows that the densities are inversely as the volumes.

Let D=density at volume V and D_1= density at volume V_1 therefore

$$\frac{D}{D_1}=\frac{V_1}{V}=\frac{1+0.00204(t_1-32)}{1+0.00204(t-32)}; \quad (4)$$

Farther let P_0 equal pressure at 32°; P that at temperature t, and P_1 that at t_1 therefore

$$V=1+0.00204(t-32)\frac{P_0}{P}V_0. \quad (5)$$

and

$$V_1=1+0.00204(t_1-32)\frac{P_0}{P_1}V_0 \quad (6)$$

hence

$$\frac{V}{V_1}=\frac{1+0.00204(t-32)P_1}{1+0.00204(t_1-32)P}. \quad (7)$$

and

$$\frac{D}{D_1}=\frac{1+0.00204(t_1-32)P}{1+0.00204(t-32)P_1}. \quad (8)$$

therefore

$$V_1=V\left(\frac{1+0.00204(t_1-32)P}{1-0.00204(t-32)P_1}\right) \quad (9)$$

and

$$D_1 = D\left(\frac{1+0.00204(t-32)P_1}{1+0.00204(t_1-32)P}\right) \quad (10)$$

Now suppose $t=32°$ and $P_1=P$ and $D=0.081$ in the last formula and we have,

$$D_1 = \frac{0.081}{1+0.00204(t_1-32)}, \quad (11)$$

from which the density of the air can be found at any temperature, the pressure P being constant.

In case it is desired to calculate the density D at any pressure whatever, we may write in the above formula where b is any height of barometer and $29.92=$ height at temperature of $32°$ and $D=0.081-$

$$\frac{P_1}{P} = \frac{b}{29.92}$$

and again taking $t=32°$ and $D=0.081$ we have

$$D_1 = \frac{0.081}{1+0.00204(t_1-32)} \times \frac{b}{29.92} \quad (12)$$

According to the law of physics, known as the principle of Archimedes, a

body plunged into a fluid loses a part of its weight equal to the weight of fluid displaced. This law may apply to three different cases :

1. The weight of the body may exceed the weight of the fluid displaced, or in other words, the mean density of the body may be greater than that of the fluid, in this case the body sinks.

2. The weight of the body may be less than that of the fluid displaced; in this case the body rises partly out of the fluid until the weight of the fluid displaced is equal to its own weight.

3. The weight of the body may be equal to the weight of the fluid displaced; in this case the two opposite forces being equal the body is in equilibrium and remains in any position in which it may be placed. (See Deschanel's Physics, Chapter IX, Principle of Archimedes).

We will consider the application of these laws in the case of common air, considering at first a single cubic foot.

It has been shown, that at a tempera-

ture of 32°, and under a pressure of 29.92 inches of mercury, every cubic foot of air weighs 0.081 pounds. While the temperature of the single cubic foot remains at that point we have, by case 3 above, a condition of equilibrium, and no movement or disturbance takes place, since an equivalent volume of the surrounding air has exactly the same weight.

Suppose, however, the temperature of the air is at 70° and that by coming in contact with some cold surface, as, for instance, a window pane, the temperature of the single cubic foot is reduced to 32°. The result of such reduction is by the preceding discussion threefold :

(1) Volume reduced,

(2) Density increased,

(3) Consequently it becomes heavier than surrounding air and tends to fall by a certain definite weight found as follows: Taking formula (11)

$$D=\frac{0.081}{1+0.00204(70-32)},$$

reducing we have

$D=\frac{0.081}{1.077}=0.0752=$the weight of a cubic foot of air at 70°.

The volume under the new conditions may be found by formula (1).

The cubic foot of air in passing from the temperature of 70° to that of 32°, increases its weight by $0.081-0.0752=0.0058$ pounds. Carrying this calculation into grains, we have weight at $70°=7000\times0.0752=526.4$ grains, weight at $32°=7000\times0.081=567.0$ grains, $567.0-526.4=40.6$ grains=gain in weight of a cubic foot of air by reduction of temperature from 70° to 32°.

In cold weather, when the windows and outside walls are much colder than the general temperature inside, it is evident from the preceding that currents of air must be continually passing downward to the floor along such cold surfaces.

Suppose, farther, the air is at a temperature of 40° and by coming in contact with a heated surface is warmed to 98°. Density at $40°=0.0797$ pounds. Density

at 98°=0.0714 pounds. Or, a cubic foot in passing from temperature 40° to that of 98° loses weight by an amount equal to 0.0797—0.0714=0.0083 pounds=7000 ×0.0083=58.1 grains. Our particular cubic foot of air is then in the condition of case 2 of the principle of Archimedes. Its tendency is to rise and it continues doing so when unconfined, until a point is reached where the densities are again equal.

The temperature of the human body is 98° while 40° is about an average temperature of the air during the whole year. It is evident, therefore, that a ventilation of the body is continually taking place through the operation of natural causes. We should take advantage of the hint thus obtained from nature, and plan the ventilation of our dwellings and public buildings upon a more rational basis than at present seems to prevail.

It is evident, without special discussion, that movements similar to those just ascribed to the particular cubic foot

of air are, in fact, constantly taking place throughout the whole atmosphere, not only out of doors but in as great a degree inside. The atmosphere, considered as a whole, can never be at rest, the slightest changes in temperature produce variations in volume, density and pressure, and these again are the causes of unending motion. In short, we may say the air is perpetually in unstable equilibrium.

The temperature at which inhabited spaces should be kept varies from 60° to 65°, depending to a considerable extent upon the nature of the operations carried on. It is certain, moreover, that the temperature can be kept lower without discomfort in well-ventilated apartments, than in those which are not well-ventilated. Upon this point the writer has recently made some investigations which may with propriety be introduced here.

The revised charter of the city of Rochester, of last year, created a Board of Health with more extended authority than that exercised by previous boards.

Among other items the new board has authority to regulate the ventilation of public school-houses throughout the city. During the past winter the writer at the instance of said board made an extended examination of all the school-buildings to the number of twenty-five, and reported thereon at length. In the course of the examination it appeared necessary to ascertain exactly the temperature at which the several rooms were kept. In going through them and using a thermometer in each it very soon became apparent that there were extraordinary variations in the temperature. The school-rooms, numbering more than two-hundred, were then supplied with thermometers, and the teachers carefully instructed as to the manner of taking observations, &c. The observations were taken ten times a day for one week, the times of taking being as follows: At the beginning of school (9 A.M.); at end of first hour (10 A.M.); before morning intermission (10.45 A.M.); after morning intermission (11

A.M.); at end of morning session (12 M.); at beginning afternoon session (1.30 P.M.); end first hour (2.30 P.M.); before intermission (2.45 P. M.) ; after intermission (3 P. M.); end of afternoon session (4 P.M.).

These observations in connection with a careful consideration of the facilities for ventilation furnished matter of the highest interest. They led, indeed, to the inevitable conclusion that in schoolhouses where the ventilation is thorough, pupils and teachers are perfectly comfortable at a temperature of 60°–62°, and that the temperatures invariably increase as perfection of ventilation decreases. So true is this that the following laws are fairly deducible, which so far as an inquiry into the ventilation of schoolhouses is concerned, may be denominated the laws of temperatures.

1. In rooms having but one outside exposure the temperature is uniformly higher than in those having two or more outside exposures, other conditions being the same.

2. Where the communication is direct by means of roomy halls between lower and upper floors, the temperature ranges higher on upper floors.

3. Of two rooms having equal exposure and equal heating and ventilating facilities, the one containing the greater number of pupils will show the higher average temperature.

4. There is a relation between inside temperature, outside temperature and outside humidity, which relation appears to be expressed by saying that inside temperature varies directly as outside humidity and inversely as outside temperature.

The writer cannot at present vouch for the entire correctness of this last law; the observations were somewhat conflicting, though the preponderance is decidedly in favor of the law. It stands at present, however, as an inference rather than a positive induction.

The temperatures show invariably an increase from beginning of school in morning (9 A.M.) to end of first hour

(10 A.M.). They also show a corresponding increase from beginning of school in afternoon (1.30 P.M.) to end of first hour (2.30 P.M.). In buildings of no ventilation, and where, during the winter, flushing with fresh air is resorted to by opening windows at intermissions, the thermometers were naturally lower after intermission than before; while in those where flushing is not resorted to, the temperatures were substantially the same. The maximums were usually obtained before intermission, and at end of session. Observations on humidity were also taken in several of the buildings, and it was found that a great increase of moisture in excess of that outside took place in poorly-ventilated rooms, pointing to the conclusion that excess of temperature is accompanied by excess of moisture, and to the farther consideration that excess of temperature, and excess of moisture are certain indications of defective ventilation.

Judging from the showing of the temperature records a great difference of

opinion exists as to the proper temperature at which a room should be kept. The rooms are undoubtedly kept at the point of comfort and that point varies as perfection of ventilation varies. For instance, the lowest temperatures occur in well-ventilated rooms, while the highest occur in those poorly-ventilated. In rooms where the temperature ranges from 62° to 66° the question was asked of the teachers in at least twenty places, "Do you find the room too warm when much above 66°? The reply usually was, "We do." In the case of rooms with an average temperature of 68°–71° the form of question was, "Do you find the room too cold when much below 68°? The reply was in nearly every case, "We do." The general principle, therefore is, in imperfect ventilation the exhalations from the body and breath produce an excess of moisture in the air, and, consequently, an increase of relative humidity. Our sensations of heat and cold depend (within limits) as much upon the amount of moisture present in

the air as upon the actual temperature. A high relative humidity always produces chilliness. We instinctively, therefore, increase the heat as the moisture increases. Moreover the air's capacity for moisture increases as the temperature. In illy-ventilated apartments, the two go together, increase of moisture leading to increase of heat, increase of heat leading to increase of moisture. Aside from the mere waste of heat resulting from this condition of affairs, there is matter of more serious import to be considered. Where bad ventilation exists the windows and doors are thrown wide open for flushing at intermissions and noontime. There results an immediate depression of temperature, in some cases sufficient to fall below the dew point, hence moisture is actually deposited as dew about the room, and hence colds and sickness of teachers and pupils generally. The same thing will occur not only in school rooms, but in any illy-ventilated apartment where a large number of people being congregated,

windows are suddenly opened for the admission of fresh air.

The question of humidities is somewhat complicated. It will be eminently proper, therefore, to consider briefly the principles involved; and in making such considerations Deschanel's Physics will be drawn upon. With this general acknowledgement such use is made of the excellent work in question as may be necessary to the proper elucidation of the subject in hand.

The condition of the air as regards moisture involves two distinct elements: (1) the amount of vapor present in the air, and (2) the ratio of this to the amount which would saturate the air at the actual temperature. There are two important laws bearing upon the subject:

1. The weight of vapor which will enter a given space is the same whether this space is empty or filled with a gas.

2. When a gas is saturated with a vapor the actual tension of the mixture is the sum of the tensions due to the gas

and the vapor separately; that is to say, it is equal to the tension which the gas would exert if it alone occupied the whole space plus the maximum tension of vapor for the temperature of the mixture.

The word *tension* means in this connection the force acting to produce expansion, as opposed to pressure, or the force tending to produce compression, or we may say the tension decreases the density of a gas while pressure increases that element.

Relative humidity is defined as the weight of aqueous vapor in a given volume of air, expressed as a percentage of the weight of vapor at saturation which would occupy the same volume at the actual temperature.

When air containing water in form of vapor is gradually cooled at constant pressure, its capacity for vapor gradually decreases until the point of saturation is reached. Any farther reduction of temperature is accompanied by a deposit of moisture. This point of deposit is called

the dew point, the relation of which to the actual temperature is shown by the humidity tables below.

There is a popular idea that air loses its moisture by heating. In fact, since moisture exists in the air, so far as known in the form of vapor and not mechanically suspended, the only way the air can lose moisture is by reduction of temperature to the dew point, and by consequent deposition in the form of dew. The effect of heating air is to increase the capacity for moisture, accompanied by decrease of relative humidity, an apparent dryness may thus be attained, although the absolute humidity remains the same as previous to the heating.

We will now consider the tables given below.

Table No. 1 is a general exhibit of the condition of ventilation at school-house No. 5, with one exception the best ventilated public building in the city of Rochester. This building is warmed by heated air, from three large radiating furnaces placed in the basement. The

heating apparatus has, however, one serious defect in not permitting an adequate supply of fresh air, owing to the supply conduit being too small. The result is that the currents of air on reaching the rooms show a temperature much higher than they should. Ventilation is by means of open fire-places in each room in which a fire is kept burning only during shool hours. The flues from the fire-places are of ample capacity to carry away the impure air, and, however crowded the rooms may be, the air is always fresh and pleasant.

Table No. 2 is a similar exhibit for school-house No. 13, one of the worst ventilated buildings in the city. This building is warmed throughout by stoves.

Table No. 3 is a similar exhibit for school No. 9, a complete discussion of which will be found afterwards.

Table No. 4 is a humidity table for No. 5, while table No. 5 is a similar exhibit for school No. 13.

The tables are generally self explanatory, though one or two points may be specially noticed.

No. 1.—Table for No. 5.

No. of grade.	No. boys belonging.	No. girls belonging.	Total No. pupils in room.	No. sittings in room.	Floor area in square feet.	Ratio of sittings to floor area, square feet.	Volume in cubic feet.	Ratio of sittings to volume, cubic feet.	Deficiency of air space for each pupil in cubic feet.	Amount of air to be supplied per hour in cubic ft.	No. changes of air required per hour.	Estimated capacity of exhaust per hour in cubic ft.	Deficiency of exhaust per hour in cubic feet.	No. outside exposures.	No. windows.	Temperature, Fahrenheit.	Maximum.	Minimum.	Range.
9th	40	29	69	55	704	12.80	9559	174	0	46750	4.9	50000	0	2	6	65.27	70	60	10
8th	25	24	49	55	749	13.62	10150	185	0	57750	5.6	60000	0	2	6	64.72	70	60	10
7th	19	18	37	53	749	14.12	10152	191	4	62010	6.1	63000	0	2	6	62.17	68	54	14
6th	28	28	56	47	704	14.99	8893	189	36	63450	7.1	65000	0	2	6	65.02	68	62	6
5th	25	31	56	49	704	14.28	8891	181	59	70560	7.9	72000	0	2	6	66.56	70	62	8
4th	21	28	49	47	749	15.94	9470	201	62	74260	7.9	75000	0	2	6	67.06	72	60	12
3d	19	31	50	47	749	15.94	9470	201	89	81780	8.6	83000	0	2	6	67.06	71	58	13
2d	16	17	33	36	704	19.55	11012	306	2	66600	6.0	45000	21600	2	6	66.39	72	58	14
1st	15	31	46	42	749	17.83	11703	279	54	84000	7.1	45000	39000	2	6	67.12	72	57	15

No. 2.—Table for No. 13.

No. of grade.	No. boys belonging.	No. girls belonging.	Total No. pupils in room.	No. sittings in room.	Floor area in square feet.	Ratio of sittings to floor area, square feet.	Volume in cubic feet.	Ratio of sittings to volume, cubic feet.	Deficiency of air space for each pupil in cubic feet.	Amount of air to be supplied per hour in cubic ft.	No. changes of air required per hour.	Estimated capacity of exhaust per hour in cubic ft.	Deficiency of exhaust per hour in cubic feet.	No. outside exposures.	No. windows.	Temperature, Fahrenheit. °	Maximum. °	Minimum. °	Range. °
9th D	24	17	41	48	343	7.35	3386	70	72	40800	12.1	0	40800	1	2	68.16	73	62	11
9th C	18	15	33	44	350	7.70	3456	79	63	37400	10.8	0	37400	1	2	67.91	78	62	16
9th B	18	20	38	40	313	7.82	3240	81	61	34000	10.5	0	34000	1	2	68.22	72	61	11
9th A	23	12	35	42	389	9.26	4292	102	40	35700	8.3	0	35700	1	4	68.64	75	62	13
8th B	24	30	54	56	781	13.95	9476	169	6	58800	6.2	0	58800	2	4	65.53	72	60	12
8th A	20	36	56	64	775	11.95	9394	147	28	67200	7.1	0	67200	1	2	70.19	78	62	16
7th	36	33	69	80	761	9.51	9200	115	80	93600	10.2	0	93600	1	2	70.05	76	56	20
6th B	20	18	38	58	775	13.36	9395	162	63	78300	8.3	21000	57300	1	2	70.41	75	63	12
6th A	23	18	41	56	794	14.18	9612	172	53	75600	7.8	21000	54600	2	5	70.35	76	62	14
5th	29	21	50	50	754	15.08	11818	236	4	72000	6.1	14000	58000	2	5	70.84	76	64	12
4th	16	25	41	46	787	17.11	12202	265	0	72680	5.9	21000	51680	1	2				
3d	29	23	52	53	772	14.56	11975	226	64	92220	7.7	14000	78220	1	2				
2d	18	10	28	42	779	18.55	12110	288	20	77700	6.4	0	77700	1	2				
1st	11	21	32	36	786	21.83	12369	343	0	72000	5.8	0	72000	2	4				

NO. 3.—TABLE FOR NO. 9.

No. of grade.	No. boys belonging.	No. girls belonging.	Total No. pupils in room.	No. sittings in room.	Floor area in square feet.	Ratio of sittings to floor area, square feet.	Volume in cubic feet.	Ratio of sittings to volume, cubic feet.	Deficiency of air space for each pupil in cubic feet.	Amount of air to be supplied per hour in cubic ft.	No. changes of air required per hour.	Estimated capacity of exhaust per hour in cubic ft.	Deficiency of exhaust per hour in cubic feet.	No. outside exposures.	No. windows.	Temperature, Fahrenheit.	Maximum.	Minimum.	Range.
9th D	32	25	57	56	416	7.43	5369	96	46	47600	8.9	48000	0	2	4	65.94	75	56	19
9th C	28	26	54	56	435	7.77	5442	97	45	47600	8.7	48000	0	1	2	67.51	75	57	18
9th B	29	17	46	56	427	7.62	5408	96	46	47600	8.9	48000	0	2	4	67.39	72	58	14
9th A	39	13	52	56	435	7.77	5442	97	45	47600	8.7	48000	0	1	2	68.64	79	57	22
8th	24	21	45	56	433	7.73	5417	97	78	58800	10.8	60000	0	1	2	67.74	76	58	18
7th	19	27	46	56	439	7.84	5492	98	97	65520	11.9	67000	0	1	2	67.93	78	56	22
7th & 6th	22	24	46	64	437	13.05	9878	154	56	80640	8.2	82000	0	1	2	68.59	75	56	19
6th	19	22	41	41	425	10.36	6208	152	73	55350	8.9	57000	0	2	4	68.17	75	60	15
5th	15	17	32	41	435	10.61	6292	153	87	59000	9.4	60000	0	1	2	68.51	72	60	12
4th B	12	15	27	41	435	10.61	6292	153	110	64780	10.2	66000	0	1	2	66.99	70	58	12
4th A	12	15	27	40	427	10.67	6255	156	107	63200	10.1	65000	0	2	4	69.11	74	60	14
3d	11	14	25	40	433	10.83	6273	156	134	69600	11.1	71000	0	1	2	69.00	75	60	15
2d	13	13	26	36	433	12.03	6273	174	134	66600	10.6	68000	0	1	2	67.68	71	59	12
1st	15	5	20	32	865	27.03	13361	417	0	64000	4.8	65000	0	1	2	68.35	74	59	15

No. 4.—Humidity Table for No. 5.

Date of observation.	Time of observation.	Grade in which observations were taken.	Barometer.	Actual temperature.	Temperature of dew point.	Force of vapor in inches of mercury.	Amount of vapor present in a cubic foot of air in grains.	Amount of vapor required to complete saturation at actual temperature in grains.	Relative Humidity.
Tuesday, March 6, 1877.	From 2 P. M. to 4 P.M.	9th		61°	42.3°	0.286	3.21	2.85	53.0
		8th		64	41.9	0.282	3.15	3.50	47.3
		7th		65	42.6	0.289	3.22	3.65	46.9
		5th		68	48.8	0.358	3.96	3.57	52.6
		4th		68	45.6	0.321	3.54	3.99	47.0
		2d		65	44.2	0.306	3.39	3.48	49.3
		1st		68	45.6	0.321	3.54	3.99	47.0
Outside Humidity for same Date.									
	11.58 A.M		30.210	20	5.5	0.060	0.71	0.59	55.6
	2.00 P.M.		30.128	22	3.5	0.069	0.80	0.61	58.4
	4.33 P.M.		30.007	25	9.0	0.067	0.68	0.68	50.0

No. 5.—Humidity Table for No. 13.

Date of observation.	Time of observation.	Grade in which observations were taken.	Barometer.	Actual temperature.	Temperature of dew point.	Force of vapor in inches of mercury.	Amount of vapor present in a cubic foot of air in grains.	Amount of vapor required to complete saturation at actual temperature in grains.	Relative Humidity.
Thursday, March 8, 1877.	From 1.30 P. M. to 4.00 P. M.	8th B		63°	46.0°	0.326	3.63	2.82	56.3
		8th A		65	50.6	0.381	4.23	2.64	61.6
		7th		70	55.0	0.442	4.87	3.13	60.9
		6th B		70	55.0	0.442	4.87	3.13	60.9
		6th A		67	52.6	0.408	4.52	2.78	61.9
		5th		71	54.5	0.435	4.78	3.47	57.9
		4th		71	53.0	0.414	4.54	3.71	55.0
		3d		71	53.0	0.414	4.54	3.71	55.0
		2d		70	52.0	0.400	4.40	3.60	55.0
		1st		70	52.0	0.400	4.40	3.60	55.0
Outside Humidity for same Date.									
	2.00 P.M.		29.569	42°	37.6°	0.243	2.83	0.47	85.8
	4.33 P.M.		29.491	43	38.6	0.252	2.93	0.48	85.9

TABLE NO. 6 *is an exhibit of the mean daily temperature in several of the school buildings in the City of Rochester for each of the days on which observations were taken. It shows unmistakably that the same cause has modified the result throughout the whole series. For instance, the range is higher on Tuesday than on Monday, lower on Wednesday, higher than Wednesday on Thursday, and generally still higher on Friday, though there are exceptions to this as will be seen by inspection.*

No. 6.

No. of School.	Monday, Feb. 26, 1877.	Tuesday, Feb. 27, 1877.	Wednesday, Feb. 28, 1877.	Thursday, March 1, 1877.	Friday, March 2, 1877.
2	64.12	65.46	64.48	65.58	66.57
3	66.35	66.83	65.62	66.46	67.16
4	65.87	66.09	65.84	66.89	66.01
5	65.01	66.06	65.54	66.51	65.54
6	67.52	68.20	67.82	67.74	67.77
8	61.25	65.05	65.05	66.60	66.17
9	68.13	68.26	67.39	67.73	68.31
11	68.26	69.75	65.56	66.00	66.44
12	66.32	66.80	66.00	66.20	67.73
13	68.21	68.62	66.99	70.16	69.06
16	69.75	71.05	70.44	71.71	71.64
17	68.26	68.40	68.24	68.31	70.38
18	67.02	67.34	67.29	68.61	68.00
19	67.30	66.71	65.69	66.12	65.66
20	65.43	67.33	65.66	67.27	68.22
Means	66.58	67.46	66.50	67.45	67.64

No. 7.

Table of amount of air to be supplied for each pupil in the different grades.

Grade.	Average age in years.	Amount of air for each pupil per hour in cubic feet.	Amount of air space for each pupil in cubic feet.
9th	6.26	850	142
8th	7.76	1050	175
7th	8.66	1170	195
6th	9.52	1350	225
5th	10.69	1440	240
4th	11.72	1580	263
3d	12.90	1740	290
2d	13.69	1850	308
1st	14.88	2000	333

The column of "amount of air to be supplied per hour," is obtained by multiplying the number of sittings in each room by the corresponding factor from the table of "amount of air to be supplied for each pupil in the different grades" (Table No. 7). This factor was obtained as follows: The empirical assumption was made that the pupils in first grades require 2,000 cubic feet of

air per hour, and that in the lower grades they require an amount proportional to their ages. The column of "amount of air space for each pupil" of this table was obtained in this way: It is well established that where change of air, in average apartments, occurs at a greater rate than six times an hour, currents and unpleasant drafts are produced, which are likely to seriously affect the occupants. The limit of space for a single person will, therefore, be the amount of air to be supplied to each person divided by six. In this way the column in question was obtained.

In tables 1, 2 and 3 the column of "no changes of air required per hour" is the number of changes required per hour to keep within the standard of ventilation here assumed.

The column of "deficiency of air space for each pupil" is a comparison between the column of ratio of sittings to volume and the "amount of air space for each pupil," and shows what addition to the volume for each sitting would be neces-

sary to bring the room within the limits of scientific ventilation.

The temperatures in tables 1–3 are the averages of all observations.

The necessary calculations of humidities are from Glaisher's tables, while the outside humidity record is from the signal service office at Rochester.

According to General Morin, the amount of air to be changed every hour, in order to keep within the limits of good ventilation is as follows :

	Cubic feet.	
Hospitals	2,119	3,709
Prisons		1,776
Workshops	2,119	3,532
Barracks	1,059	1,776
Theatres	1,413	1,776
Lecture and assembly rooms, &c.	1,059	2,119
Schools	424	1,059

Having decided how much air shall be supplied per unit of time, the next question is how shall the supply be furnished ? This introduces us to our subject proper, *The Mechanics of Ventilation.*

Two methods of producing the result may be distinguished, the *vacuum* and the *plenum*. We confine ourselves entirely to a consideration of the former, as being more in accordance with the natural order of affairs, and as having been demonstrated by experience to give the better results.

The vacuum method requires that every apartment or building shall have, suitably connected with it, a vertical shaft, in which an exhaust draft is constantly maintained. The problem in hand, then, is the determination of the dimensions of such a shaft and its contingent connections, together with such special considerations as shall make the method applicable to any case whatever.

The points of withdrawal will be as near the source of contamination as convenient, that is, at or near the floor. They should never be in the floor itself, as dust, etc., will collect ultimately causing unpleasant stoppages. The points of ingress should, on the contrary, be as far away from the contamination

as possible, or at the ceiling. It may be taken as a general law that whatever the method of heating resorted to, foul air should be drawn out of a room by creating a vacuum at some point in the side walls near the floor, while fresh air should be introduced at or near the ceiling.

We have seen that heating a limited amount of air to a temperature higher than the surrounding atmosphere causes the heated portion to ascend. This then offers in many cases a cheap and efficient means of ventilation, by simply utilizing the large amount of heat now wasted through the chimneys. It should be noticed in passing that although there is a great waste of heat at present through the chimneys, it seems certain that improved ideas of chimney building will soon in a great degree correct that evil. In the meantime, the ventilation of structures already erected may be improved by taking advantage of the method here indicated.

The formula expressing the conditions

of movement of heated air in a vertical flue is

$$V = E\sqrt{2g\frac{ha\,(t'-t)}{1+at'}} \quad . \quad (13)$$

where the notation is

V=velocity of ascent of air current per second.

E=a numerical coefficient, constant for each shaft, and expressing the reduction of the theoretical velocity due to friction, eddies, &c.

g=the acceleration of gravity numerically equal to 32.2 ~~lineal feet~~.

h=the height of the chimney or flue, and the consequent height of the confined column of air.

a=coefficient of expansion of air =~~0.00204 as previously given.~~ .00217

t'=temperature within the chimney, and

t=temperature of outside air.

This formula is merely an expression in extended form of Torricelli's theorem, which asserts that the velocity of any freely falling body is equal to the square

root of twice the acceleration of gravity, into the height through which the body falls. Expressing this more elegantly as an equation, and we have

$$V=\sqrt{2g\,h'} \quad . \quad . \quad . \quad (14)$$

where g has the value just given and h' is the height through which the body falls.

In formula (13)

$$\frac{ha\,(t'-t)}{1+at'}=h\frac{1+at'}{1+at'}+h=h' \quad . \quad (15)$$

We have seen by previous discussion that when air is heated at constant pressure the volume increases. Now in case the heating takes place in a flue open only at the ends, it is evident the expansion must cause an increase in the length of the confined column. Such increase is expressed by h'. Moreover the difference between the original length of the column at temperature t, and the new length at temperature t', is equal to the height through which a volume of outside air equal to the original volume within the flue has fallen, to produce the

upward movement within the flue; h' is, therefore, the head of fluid producing pressure, and may be calculated by the general formula for head of fluids flowing through pipes, &c., following:

$$h' = \left(1 + \xi_1 + \xi_0 + \left(\xi \frac{l(a+b)}{2ab}\right)\right) \frac{V^2}{2g} \quad (16)$$

This formula means, that having given the cross-section of a flue, pipe or conduit, and the amount of air to pass through per unit of time, which of course determines the velocity V, per unit of time, the height of column of air necessary to produce the velocity V, through the given cross-section, is equal to h' as expressed by the above formula, the notation of which is as follows:

h' has the value previously given.

ξ_1, ξ_0 and ξ are coefficients of resistance of elbows, efflux and influx and friction respectively.

l=length of pipe.

a and b=dimensions of cross-section.

V=velocity of current per unit of time, and

g=acceleration of gravity as previously given.

In case the flue is cylindrical the expression

$$\left(\xi\frac{l(a+b)}{2ab}\right) \text{ will become } \xi\frac{l}{d}.$$

General formula for velocity is

$$V=\frac{Q}{F} \quad . \quad . \quad . \quad . \quad (17)$$

where Q=quantity discharged per unit of time, and F=sectional area of duct.

Formula (13) enables us to say what the conditions of discharge are in a vertical flue. It depends upon :

1. The height h; that is the power of the flue, or its velocity of discharge, increases as the square root of the height increases, the difference of exterior and interior temperatures remaining constant.

2. The square root of the difference of t' and t; that is with a given height of flue the velocity of discharge will increase as the difference between interior and exterior temperatures increases.

3. The resistance to ascent of currents of air by friction and eddies; that is the velocity of discharge, will increase as the smoothness, straightness and adaptation of the cross-section of the flue to the amount of air to be disposed of increases.

It follows from these conditions that having the height, sectional area and general arrangement of any chimney or flue, the quantity of air or products of combustion discharged per unit of time will always be the same, provided the excess of temperature inside the chimney over that of the outside air remains constant.

We will now make a numerical application of the principles here set forth; the example selected for such purpose being school building No. 9, in the city of Rochester.

The object in taking this particular case is that a system of ventilation by the vacuum method was recently constructed at that building. Owing, however, to neglect of the principles here set

forth, hardly moderate success was attained. The discussion will therefore include not only the numerical application to that building, but also critical notes on the ventilating works as they were actually carried out.

By referring to the table No. 9, given above, it will be seen that the building contains fourteen rooms, and that the amount of air to be renewed per hour is 837890 cubic feet. The volume of halls is in round numbers 7000 cubic feet. Adding for change of air about twice each hour in halls, and we may take the total amount to be renewed per hour at 850000 cubic feet. The building is two stories high, having seven rooms to each floor, and is L shaped, fronting upon two streets. In the inside angle of the L a shaft fifty-five feet in height was erected, straight inside, with sectional area top and bottom equal to 26.62 square feet. From the foot of the shaft large ducts were carried to either extremity of the L. The main ducts were ($20'' \times 44''$); second-

ary ones ($16'' \times 36''$); tertiary ones ($16'' \times 22''$); and so on, decreasing as distance from main shaft increased. Into these horizontal ducts were let vertical ones which connected with the rooms by openings in floor, over which iron registers were set. The number of openings and corresponding ducts from each room is six. Sectional area of each of these small ducts ($6'' \times 8'' = 48$ square inches. The elbows are in every case square. The number of small ducts leading to halls is 13, and since there are 6 to each room, and 14 rooms the total number of exhaust openings is found to be 97. We will assume for present purposes that the openings have equal capacities, though the variations of resistance, because of elbows and difference of length of small ducts leading to main ducts in cellar, give them in fact, varying capacities. On this assumption each duct will take away a quantity per hour equal to

$$\frac{850000}{97} = 8763 \text{ cubic feet.}$$

The amount removed per second by a single duct will be

$$\frac{8763}{3600}=2.434 \text{ cubic feet.}$$

According to formula (17)

$$V=\frac{2.434\times 1728}{6\times 8\times 12}=7.3 \text{ lineal feet.}$$

In fact the free area of opening is not more than two-thirds of the sectional area of pipe, owing to the register set over the opening. Or the velocity through register will be

$$\frac{4206}{32\times 12}=10.9 \text{ lineal feet.}$$

The velocity of 7.3 lineal feet per second will therefore be in the pipe under the register, and the discussion may be continued on the supposition that the register is absent by using a sufficiently large value for the coefficient of influx in the expression for head following.

Then if resistance from friction and elbows and all other sources of resistance were entirely eliminated the head necessary to produce a velocity of 7.3

lineal feet per second throughout the small ducts would be sufficient to exhaust all the impure air. In fact, the reduction for friction, elbows, etc., gives us widely varying velocities for different parts of the ducts, and requires in every case an addition to the head.

To find head$=h'$ we take formula (16) and using the following values :

$$\xi_1 = 0.840,$$
$$\xi_0 = 1.750,$$
$$\xi = 0.0205,$$
$$l = 36,$$
$$a = 6'' = 0.5 \text{ feet},$$
$$b = 8'' = 0.66 \text{ feet},$$
$$V^2 = (7.3)^2 = 53.29,$$
$$2g = 64.4,$$

we have

$$h' = \left\{ 1 + 0.840 + 1.750 + \left(0.0205 \frac{36(0.5+0.66)}{2(0.5 \times 0.66)} \right) \right\} \frac{53.29}{64.4}, \quad \therefore$$

$$h' = 4.04$$

Applying similar reasoning to the main ducts in basement and complete expres-

sion for h' aside from the vertical exhaust flue is found as follows :

$$h' = 4.71 \text{ feet.}$$

According to formulæ (1) and (2) illustrating Gay Lussac's law for constant pressure, the volume of one and the same quantity of air increases or decreases directly as the temperature.

The average temperature of the air in the school-rooms was found to be 68°, while the temperature at the foot of the main shaft was found to be from 52° to 56°, average 54°. The air had lost then in passing to that point 14°. This reduction of temperature mainly took place in the main ducts in basement, the volumes of which equal say 1500 cubic feet.

Suppose 1500 cubic feet of air at 68° to pass into the main ducts in basement, and there become cooled to 54°, a reduction of volume takes place found by formula (1) thus :

$$V_0 = 1500 \text{ cubic feet}$$
$$t = 54°$$

In place of 32° in the formula substituting 68° the temperature at which $V_0=1500$, and, because the volume at a reduced temperature is required, changing the signs of t and 68° and changing the sign of a, we have for value of V at 54°

$$V=1-0.00204(68-54)\,1500=0.97144\times 1500,\ \therefore$$

V = 1457 cubic feet,

and 1500 − 1457 = 43 cubic feet.

We see, therefore, that a vacuum is continually forming in the main ducts and adding materially to the exhausting capacity of the works. For this reason the ventilation will probably work more freely in winter than in summer, unless means are provided to raise the temperature in main exhaust flue in a corresponding ratio during the latter season. Taking formula (15)

$$h'=\frac{ha(t'-t)}{1+at}$$

it is required to find the value of t', which will produce h' as found by pre-

vious calculation. Substituting numerical values as follows :

$$h' = 4.71,$$
$$h = 55,$$
$$t = 54,$$
$$a = 0.00204,$$

and we have—

$$4.71 = \frac{55 \times 0.00204\,(t' - 54)}{1 + 0.00204 \times 54}, \quad \therefore$$

$$4.71 = \frac{0.1122\,t' - 6.058}{1.11}, \quad \therefore$$

$$5.228 = 0.1122\,t' - 6.058, \quad \therefore$$

$$0.1122\,t' = 11.286, \quad \therefore$$

$$t' = 101°.$$

101° is then the constant temperature at which the air in vertical shaft is to be kept in order to produce the action through the ducts of a head equal to 4.71 feet.

It should be remembered that this calculation involves the supposition that the pressure is that due to the air at 54°. This supposition is only partly true, as the outside temperature will at different

times vary widely from that point. The instability of equilibrium will extend itself not only to the air in the ducts and building, but also to every particle of outside air. The actual effect will depend upon a variety of circumstances, as, for instance, the constancy of supply of outside air, the method of introducing it, the temperature at which the outside air is delivered, the closeness of fitting of doors and windows and the tightness of the ducts, &c. For summer ventilation an increase of heat over that necessary for winter ventilation will be required. The capacity of the heating apparatus at foot of main shaft should, therefore, be in excess of winter requirements.

We have seen that in fact the original volume of 850,000 cubic feet per hour must be considerably less than that amount when reaching the foot of the main shaft, by reason of reduction of temperature. In order to make adequate provision for summer ventilation we will continue the discussion on the supposi-

tion that we have to deal with a volume of 850,000 cubic feet at foot of main shaft.

To raise 850,000 cubic feet from 54° to 101° will increase its volume to 931,498 cubic feet. Discharge per second then, equals

$$\frac{931498}{3600}=259 \text{ cubic feet.}$$

h' as found above equals 4.71 feet, also

$$h'=\frac{ha(t'-t)}{1+at}$$

therefore substituting in formula (13), for the present neglecting E, and we have

$$V=\sqrt{64.4\times 4.71}=\sqrt{303.324}, \quad \therefore$$

$$V=17.41 \text{ lineal feet.}$$

Since E was neglected we have 17.41 lineal feet as the theoretical velocity which will produce the necessary exhaust. Experiment indicates a reduction of the theoretical velocity in this flue of .12 for friction and eddies, consequently the actual velocity with a head of 4.71 feet, or what is the same with the flue

heated to a point to produce that head, will be $0.88 \times 17.41 = 15.32$ lineal feet. But a velocity of 15.31 feet in the vertical flue corresponds to a reduction of velocity in the ducts, we must therefore, increase h', and consequently t' by an amount sufficient to produce an actual velocity of 17.41 lineal feet per second. To calculate that increase we have 17.41 equals required actual velocity, consequently, corresponding theoretical velocity will be

$$\frac{17.41}{0.88} = 19.78.$$

The value of h' which will produce a theoretical velocity of 19.78 lineal feet will be found by taking—

$$19.78 = \sqrt{64.4 \times h'}.$$

Squaring this equation—

$$391.24 = 64.4 \times h', \therefore$$

$$h' = \frac{391.24}{64.4} = 6.07 \text{ feet.}$$

It has been shown by what has preceded that the value of t' depends upon the value of h'. It will be necessary

then, to find a new value of t' to correspond with the value of $h'=6.07$. This will be found as in the preceding case by substituting in formula (15), whence we have for ultimate value

$$t'=114°.$$

To prove the correctness of these calculations we substitute complete values in formula (13), giving

$$V=0.88\sqrt{64.4\,\frac{55\times 0.00204(114-54)}{1+0.00204\times 54}},$$

whence by reduction

$V=17.41$ lineal feet as previously found.

Translated from algebraic into common language, the preceding discussion means that a confined column of air at a temperature of 54° and original height of 55 feet, when heated to a temperature of 114° expands to a height of $(55'+6'.07)=61.07$ feet. But the height of the flue remains constant at 55 feet. The heated confined column then, when issuing from the flue becomes immediately cooled. The 55 feet of air in the

flue is lighter than the outside air, by the weight of a column of the density of the confined column and 6.07 feet in length. According to the principle of equilibrium of fluids, the confined column must rise 6.07 feet in seeking such equilibrium, or, what amounts to the same thing, the outside air falls by approximately that amount.

We are now able to say what sectional area of shaft is required. By transposition of general formula (17) for velocity we have

$$F=\frac{Q}{V},$$

that is to say, the sectional area equals the quantity per unit of time, divided by the velocity per unit of time, therefore

$$F=\frac{259}{17.41}=14.9 \text{ square feet.}$$

As already stated the shaft is constructed with cross-section equal to 26.62 square feet.

Attention may here again be called to the fact that theoretically, velocity in

the shaft is entirely independent of the cross-section, depending as previously shown, upon temperature, height and adaptation. In practice, however, it will be found of the greatest importance not to have the shaft larger than careful calculation shows necessary. Indeed the case of a confined column in motion by excess of temperature is one where it is absolutely better to have the shaft smaller than calculation shows, rather than larger. If the flue has less sectional area the required discharge may still be produced by increasing the heat, so attaining higher velocities. If, however, the sectional area is greater than really necessary, the following condition of affairs results: The current of hot air passes up along the axis of the flue, while at the sides a current of cold air passes down. The result is the production of eddies and unnecessary cooling of the confined column.

An experiment at No. 9 aptly illustrates the point in question. Temperature of air entering the shaft 52°; tem-

perature eight feet above fire 120°. The air had then been raised through 68°. This would be ample were the shaft of proper size to produce the necessary exhaust. A piece of tissue paper thrown into the middle of the ascending current and remaining there was carried to within ten feet of top of shaft in three seconds. The motion was however very irregular. When at the above point the slip was caught in an eddy and brought back to foot of shaft, was there secured and again sent up. The second time it maintained its position in the middle of the flue and passed out at the top in a little more than four and one half seconds. Repetition of this experiment under many different conditions showed that with a difference of temperature of 50° at the foot of the shaft the lightest tissue paper would rise less than one half the length of the shaft, while with a difference of from 30° to 40°, 10 to 15 feet was the extent of its rise.

We have in these experiments a significant explanation of the cause of smoky

chimneys. A chimney has usually a certain specified work to perform, and like every other contrivance for the performance of work will obey the law of adaptation. In short, even in the construction of apparently so simple a thing as a chimney, it is unsafe to set at nought nature's universal laws.

We see farther that the expedient of constructing everything a little larger than necessary, in order to have a reserve for contingencies, is not always a safe one after all.

The following criticisms can be justly made of the No. 9 ventilating arrangements as they at present stand.

1. The vertical shaft has too great a sectional area.

2. The square elbows add greatly to the resistance. An increase of power is thereby necessitated to perform the work.

3. The ducts leading from the rooms are too small, for two reasons: first, to carry away the maximum amount with their present cross-section requires so

high a velocity of influx as to be uncomfortable to the occupants; second, friction is greater in small pipes than in large ones, as may be shown by the following: The height of resistance of friction, due to dimensions of pipe and to velocity of discharge, in a round pipe is expressed by formula thus:

$$h_0 = \xi \times \frac{1}{2g} \times \left(\frac{4}{\pi}\right)^2 \times \frac{lQ^2}{d^5}$$

where ξ = the coefficient of friction determined by experiment, l = length of pipe, d = diameter and Q = discharge.

Let h_1 = the height of resistance of friction, &c., for a pipe of length also equal to l and diameter equal to $2d$, the discharge to be Q as above, then,

$$h_1 = \xi \times \frac{1}{2g} \times \left(\frac{4}{\pi}\right)^2 \times \frac{lQ^2}{(2d)^5}.$$

dividing

$$\frac{h_0}{h_1} = \frac{\xi \times \frac{1}{2g} \times \left(\frac{4}{\pi}\right)^2 \times \frac{lQ^2}{d^5}}{\xi \times \frac{1}{2g} \times \left(\frac{4}{\pi}\right)^2 \times \frac{lQ^2}{(2d)^5}},$$

whence by reduction

$$\frac{h_0}{h_1} = \frac{32}{1}, \quad \therefore$$

$$h_0 : h_1 :: 32 : 1,$$

that is, the friction in the small pipe is 32 times what it is in a pipe of double the diameter, the discharge being constant. In the same way it can be shown that with a diameter three times as great the friction would be as 3^5 to 1 or as 243 to 1 and so on.

4. The exhaust openings into the rooms are directly in the floor; the pipes, therefore, soon become filled with dust and papers.

5. The small ducts leading to the rooms are all of a size, whereas, they should increase according to the law of friction as distance from the vertical flue increases.

6. The form of shaft is faulty. It should be smaller at the top than at the bottom to compensate for the inevitable shrinkage of volume of the air current, resulting from loss of heat by radiation.

We will now determine the amount of coal which when burned will produce the necessary head.

A pound of coal contains on an average 14,500 pound-degrees or heat-units, that is, the heat from the combustion of one pound of coal will raise 14,500 pounds of water 1°, or, what is the same will raise one pound of water 14,500°. Specific heat of air is 0.238 when water is unity; or more clearly, to heat a pound of air from any temperature a, through a given number of degrees b to a temperature $a+b$, will require only 0.238 as much heat as would be necessary to raise a pound of water through the same number of degrees.

As already noted the air arrives at the point of heating—the foot of the shaft—at a temperature of 54°. It is required to raise it to 114°, or through 60°. To raise one pound of air 60° we have $1\times60\times0.238=14.28$ heat-units. Farther a pound of air at 32° equals 12.34 cubic feet, therefore by formula (1) we have for volume at 54°

$$V=[1+0.00204(54-32)]12.34, \therefore$$

$$V=12.89 \text{ cubic feet.}$$

850000 cubic feet of air at temperature 54° will equal

$$\frac{850000}{12.89}=65865 \text{ pounds.}$$

The number of pound-degrees required per hour will be

$$65865\times 14.28=940552.$$

The number pounds of coal required for seven hours, the time ventilation is required each day, will be

$$7\left(\frac{940552}{14500}\right)=454 \text{ pounds.}$$

There is, however, a certain loss of heat by conduction through the walls of the flue, determined by the formula

$$Q=ka\frac{t'-t}{d} \qquad (18)$$

in which the notation is as follows:

Q=quantity of heat conducted away per hour.

k=coefficient of conduction=0.085*.

* For values of k for various materials, see volume 2, Weisbach's Mechanics.

a=area of interior surface of the flue
=1135 square feet,
t'=inside temperature=114°,
t=outside temperature, taken at 32°,
d=thickness of wall=0.35 feet.

Substituting numerical values and making the expression for loss during seven hours, gives,

$$Q=7(0.085\times 1135)\frac{114-32}{0.35},\therefore$$

$$Q=158228 \text{ heat-units},$$

requiring a consumption of coal to make good this loss of

$$\frac{158228}{14500}=10.8 \text{ pounds.}$$

Adding this to the above and we have 465 pounds of coal=total consumption each day.

The question naturally arises how shall this heat be applied? Obviously there is no loss of heat except as just indicated by conduction. The heat may be applied then, by large grate or by furnace, with ample opening for draught,

and with smoke-pipe of large diameter extending to within 15 feet of top of flue.

One point in particular brought out by studying this system of ventilation is worthy of careful attention, namely: To ventilate a building means there is work to be done. The performance of work requires an expenditure of force, therefore, any system professing to secure ventilation without performing work, or what is the same, without expending force, is without effect.

It is not denied that natural ventilation may at times prove efficient, though it is so uncertain in its action that in buildings of any size it is practically useless.

The ventilation of a building should be like its water supply and sewerage, always ready for work and certain in its effects. When buildings are erecting such a condition can be attained at moderate expense, while it may be exceedingly difficult to accomplish after the completion. It is, then, of the high-

est importance that ventilation be considered in connection with design.

The warming at No. 9, is by stoves in each room. A cylinder of galvanized iron is placed about the stoves, thus converting them into hot air furnaces, the air in which may be taken as a heated confined column. Fresh air is introduced at floor from outside, by ducts of sectional area $(12'' \times 16'') = 192$ square inches, and from 2 to 3 feet in length. Average temperature of air in cylinder 220°, outside temperature taken at 32°. Cylinders from 6 to 8 feet in height. Velocity of inflow is found by formula (13). Amount of inflow under the most favorable conditions equals 21.5 cubic feet per second, giving a supply of 67,400 cubic feet per hour for each room.

This is a cheap way of improving the warming of a building already furnished with stoves. The diameter of the cylinders should be at least 2 feet greater than that of the inclosed stove, and their length should be nearly equal to the height of the room. The inflow duct

should be of ample cross-section and provided with a slide in order that the supply may be regulated. The supply in any case should be sufficient to prevent the temperature of the issuing air rising much above 120°.

The amount of air required to support combustion may be calculated as follows: Let the amount of air to be supplied to any room be 65,000 cubic feet per hour or 455,000 cubic feet for seven hours, or in the same proportion for any number of hours, then

$$\frac{455000}{13.0} = 35000 = \text{number of pounds to}$$

be supplied for seven hours at temperature of 60°.

We will take outside temperature at 32°, and for purposes of this calculation, in order to make an allowance for loss by radiation, we will take the temperature to which the air is to be raised at 75°. This would involve raising the temperature through 43°. The number of heat-units required per day of seven hours, therefore, will be

$$35000 \times 43 \times 0.238 = 358190.$$

The daily consumption of coal under the above conditions is

$$\frac{358190}{14500} = 24.7 \text{ pounds.}$$

Observation and calculation have demonstrated that the amount of air required to consume a pound of coal is on an average 150 cubic feet. From imperfection in burning appliances, etc., the consumption frequently rises above twice that amount, and 300 cubic feet to the pound is generally used for these calculations. We have for the consumption during seven hours

$$24.7 \times 300 = 7410 \text{ cubic feet.}$$

In applying this matter practically it must be borne in mind that usually *larger quantities* will be needed than calculation indicates unless very liberal allowances for loss by radiation and conduction are made.

A new phase of ventilation has recently been developed by a German philosopher,

Pettenkofer by name, who found that by diffusion alone, the air of a room in his house (cubic contents 2650 feet) was changed once every hour when the difference of exterior and interior temperatures was 34°. With the same difference of temperature, but with the addition of a good fire in the stove, the change rose to 3320 cubic feet per hour. With all the crevices and openings about doors and windows pasted up air tight the change amounted to 1060 cubic feet per hour. With a difference of 40° between exterior and interior temperatures the ventilation through the walls amounted to 7 cubic feet per hour for each square yard of wall surface. The practical deduction from which is, that ventilation may be much improved by merely increasing the amount of free wall surface. In designing school houses, particularly, such an arrangement should be adopted as will insure at least two outside exposures, thus giving not only better ventilation,

but also rendering it certain that a sufficient supply of light be admitted.*

One way of applying the vacuum method of ventilation is to carry the smoke flue from furnace in basement up through a vertical shaft from which openings into the rooms are made. Several examples of this form of construction recently examined by the writer have the smoke flue of vitrified sewer pipe. This offers a cheap method of forming the flue, though it can scarcely be recommended on account of the low conducting power of the material, the conducting power of fire-clay, the main material of vitrified pipe, being 39.6 less than that of wrought iron.

An important application of the formulæ for confined columns, etc., may be made in designing the flues for hot air in buildings warmed by furnaces. The method quite frequently followed at present is to make the flues leading to the various stories of a building all of

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* Hartley's Lectures. "Air and its relation to life."

the same size, and this without reference to the horizontal distance from the source of supply. The result of this unscientific proceeding is that down currents are created in the pipes leading to the lower stories. To remedy this difficulty it is customary to introduce slides into the longer flues by which a part of their capacity may be cut off. A curious misapplication of the above practice recently came to the writer's notice. School-house No. 11 is a new building, occupied about January 1st. It was found that no hot air could be brought into the rooms of the first floor, and that currents of air actually passed from those rooms into the flues. An examination into the matter revealed the fact that, the flues for the different floors were all of the same size and that the slides for regulating the supply had been placed in those leading to the first floor instead of to the floor above. The result was as just stated, the air passed from the rooms of the first floor into the flues leading to that floor, down to the fur-

nace, and then up to the second floor. The first floor was, therefore, ventilated directly to the second, a condition of affairs neither conducive to comfort on the first floor nor good health on the second.

Obviously the better way is to decide how much air each flue is required to supply, and then apply the formulæ above given for cross-section, &c. In this way a constant balance of forces may be maintained.

It is a well-established principle of mechanics that every force acts along the line of least resistance, and no better illustration of its truth can be found than in the application of the laws of movement of heated, confined air-currents.

In order to farther illustrate the theory of ventilation as here set forth, a numerical application will also be made to the Assembly room in the city building of the City of Rochester.

Preliminary data is as follows :

Length =108′ 0″
Breadth= 78′ 0″
Height = 27′ 0″

Floor area, with an addition for stage =8831 square feet.

Total volume, including stage, without deduction for furniture, &c.=244,949 cubic feet.

The seats now in place accommodate comfortably 1200 people, with standing room for 400 more. Total capacity is therefore taken at 1600. Deducting one-half cubic foot for each seat, and 3 cubic feet for space actually occupied by each person, and making other deductions for cornices, raised floor at sides and ends, projection of stage into room, etc., and we have an available volume of 230,500 cubic feet.

Under the above conditions the floor area for a single person will be

$$\frac{8831}{1600}=5.52 \text{ square feet;}$$

while the volume for each person will be

$$\frac{230500}{1600} = 144 \text{ cubic feet.}$$

Lighting apparatus consists of 112 gas burners, each consuming 4 cubic feet of gas per hour. The consumption of gas per hour, then, is $112 \times 4 = 448$ cubic feet.

As previously shown a cubic foot of gas in burning produces 0.43 cubic feet of carbonic acid. Production of carbonic acid per hour from combustion of gas, therefore $= 448 \times 0.43 = 192.6$ cubic feet. Each person produces 0.6 cubic feet of the same gas per hour. Production from respiration, then $= 960$ cubic feet. Total amount of carbonic acid per hour $= 960 + 192.6 = 1152.6$ cubic feet.

Assume the heat from a single person to be 475 units per hour, and the heat from combustion of a cubic foot of gas to be 750 units: We have

$1600 \times 475 = 760000$ heat-units per hour from the audience; and from the lights

$448 \times 750 = 336000$ heat-units per hour, making a total production per hour of

1096000 heat-units.

Suppose the air supply to be at a temperature of 62° and equal to 2000 cubic feet per hour for each person, the amount per hour will be

$$1600 \times 2000 = 3200000 \text{ cubic feet.}$$

The amount of heat required to raise a single cubic foot of air 1° at an original temperature of 60° or thereabout is

$$0.0766 \times 0.238 = 0.01815 \text{ units.}$$

The increase in temperature of the air supply, due to the heat from lights and people will be found as follows:

$\frac{3200000}{13} = 246154$ pounds of air per hour, and

$\frac{1096000}{246154} = 4.4 =$ number of heat-units to eaeh pound of air.

A single heat-unit raises one pound of air through

$\frac{1.0000}{0.238} = 4°.2$ actual temperature.

The increase of actual temperature of whole supply will therefore be

$$4.2 \times 4.4 = 18°.48.$$

On the supposition that the adjustment of supply to exhaust is properly made the air on leaving the hall must have a temperature of

$$62° + 18°.48 = 80°.48.$$

The exit per second will equal

$$\frac{3200000}{3600} = 888 \text{ cubic feet.}$$

Assuming the velocity of exhaust in vertical flue to equal 20 feet per second, we have for area of said flue

$$\frac{888}{20} = 44.4 \text{ square feet,}$$

or what would be preferable, two flues each with area of 22.2 square feet. Assume farther that the inflowing air shall have a velocity of 4 feet per second, the area of inlets will be

$$\frac{888}{4} = 222 \text{ square feet.}$$

Assume a sectional area of 6 square feet for each inlet, and

$$\frac{222}{6}=37=\text{number of inlets.}$$

Assume again that velocity in outlets is 6 feet per second,

$$\frac{888}{6}=148 \text{ square feet}=\text{area of outlets.}$$

Also let area of each outlet be 6 square feet, same as inlets

$$\frac{148}{6}=25 \text{ number of outlets.}$$

The discussion has taken no account of the increase in volume due to the increase of temperature. Were such account taken the dimensions of outlets would be somewhat increased.

The number of changes per hour under the above conditions may be determined by two methods, either by dividing the supply per hour for each person by the volume for each person, thus,

$$\frac{2000}{144}=13.9$$

or by dividing the total supply per hour

by the total available volume of the hall, thus,

$$\frac{3200000}{230500} = 13.9$$

giving the same result in either case.

The discussion has also proceeded upon the supposition of no loss by conduction and radiation. We will now consider the modifications of the above calculations due to these sources of loss.

The hall is warmed by steam, direct radiation. Number of sets of radiators 18, each having an area of 60 square feet. Total radiating surface, therefore,

$$60 \times 18 = 1080 \text{ square feet.}$$

Amount of space heated by one square foot of surface equals

$$\frac{230500}{1080} = 213.4 \text{ cubic feet,}$$

which is certainly ample for the coldest weather likely to be experienced here.

To find loss by conduction through walls and windows, we will assume inside temperature at a mean between

temperature of entering air and temperature to which it is raised by heat from persons and lights, or say at 71°. Outside temperature is taken at 32°. The outside exposures are three in number, two sides and one end. We will consider the loss of heat only from the three outside exposures, neglecting the protected end, ceiling and floor.

Area of the three exposed sides exclusive of windows=6306 square feet. Area of windows=1696 square feet.

Taking formula (18) we have for the loss through walls exclusive of windows:

a = 6306 square feet,

t'= 71°,

t = 32°,

k = 0.095,

d = thickness of wall=2 feet,

then

$$Q=0.095\times 6306\frac{71-32}{2}=11487=$$ number of heat-units conducted away through walls per hour.

For windows we have

$$a = 1696,$$
$$t' = 71°,$$
$$t = 32°.$$

Experiments have been made in the case of window glass, showing that neglecting d the value of k varies from 1 to 3. We will take it for this calculation at a mean value, namely, 2. We have therefore

$$Q = 2 \times 1696(71 - 32) = 132288.$$

hence the total loss by conduction per hour under the conditions of temperature assumed is

$$11487 + 132288 = 143775 \text{ heat-units.}$$

Suppose however, instead of allowing 2000 cubic feet per hour for each person, we take what is more nearly the actual supply, that is 850 cubic feet. With that assumption we have a total supply per hour of 1,360,000 cubic feet. The amount of heat from people and lights will be the same as before. Assume temperature of air supply at 62° as previously. Amount of air in pounds

$$\frac{1360000}{13}=104615.$$

Number of heat-units per pound of air is

$$\frac{1096000}{104615}=10.4,$$

making an increase of actual temperature of

$$10.4\times 4.2=43^{\circ}.68.$$

Assuming no loss by conduction and radiation, and the temperature of the outflowing air is

$$62^{\circ}+43^{\circ}.68=105^{\circ}.68.$$

In fact loss by conduction, &c., increases in proportion as inside temperature increases, consequently the amount conducted away will be correspondingly greater than in the preceding case. Observation will show air in upper part of room to range from 85° to 95°. The writer has on several occasions observed it higher than 80° in lower part of room, and this too with windows open, and outside temperature at from 35° to 40°.

A partial exhibit has now been made

of the main principles underlying the Mechanics of Ventilation. In conclusion it will be well to collate principles and facts for convenience of reference.

1. Perfect ventilation is hardly automatic. A certain amount of attention is necessary to keep any system in working order.

2. Ventilation by draught is preferable to ventilation by forcing air in, it having the advantage of supplying fresh air as fast as foul air is removed, provided of course the design is properly carried out.

3. The vacuum may be produced in the case of rooms or suites of apartments by fire-places or by small flues properly connected with the rooms at or near the floor, in which gas jets are kept burning whenever ventilation is needed. In large buildings, however, the vacuum will of necessity be produced by vertical shafts designed in accordance with the principles herein contained.

Corollary.—Where gas jets are used the amount of heat from one cubic foot of gas may be taken as given in the begin-

ning of this paper. Knowing the amount of air to be carried away per hour, the size and number of burners is easily found.

4. Perfect ventilation will cost something. To lift a thousand pounds of air 50 feet, requires exactly the same expenditure of force as to lift a thousand pounds of iron, or any other substance 50 feet.

Corollary 1.—Since to ventilate a building means there is work to be done, and consequently an expenditure of force necessary, any system professing to ventilate without such expenditure of force can hardly be other than a failure.

Corollary 2.—Careful study of the matter shows the importance of reducing friction in flues, ducts, elbows, etc., to a minimum; otherwise a large percentage of force will be expended for that purpose only.

5. Ventilation is a branch of mathematical investigation, actual construction should, therefore, be preceded by careful calculation.

6. Heating is a branch of ventilation and should always be considered in connection with it.

Corollary 1.—In warming by heated air the current should be introduced at or near the ceiling. It is a violation of first principles to introduce it near the floor.

Corollary 2.—In designing a system of warming by heated air, provision should be made for introducing cold air in connection with the warm current, in order that the air may not enter the room at too high a temperature.

Corollary 3.—The cold air currents as per Corollary 2 should be under perfect control as well as the heated currents, in order that the proper temperature inside may be maintained under every variation of outside temperature.

Corollary 4.—Warming by steam or hot water, by a combination of the two, or by steam and hot air combined may all be exceedingly healthful, provided adequate ventilation accompanies them. These methods are all reasonably economical as regards consumption of fuel.

Corollary 5.—Warming by ordinary stoves cannot be considered desirable except on the score of economy. The objections to their use are :

(1) Difficulty of producing ventilation in connection with the warming.

(2) Cast iron, the usual material for their manufacture, when red hot allows the gases, carbonic acid and hydrogen to pass through into the rooms.

(3) The heat is irregularly distributed causing great variations in temperature in different parts of the rooms.

7. It should be understood that ventilation by opening doors and windows is nearly as bad as no ventilation.

8. In large buildings much satisfaction, and what at the present time is of the greatest importance, much valuable information could be obtained by putting up in connection with such a system of ventilation by the vacuum method, apparatus for determining and accurately registering the results under varying conditions of outside and inside temperature. An anemometer in the main shaft

with electric recording apparatus in the superintendent's office, would show at any instant exactly the condition of the ventilation. In this way regularity of action will be assured, and at the same time a collection of data of the greatest value in future building operations can be made.

Farther, in conclusion it may be stated that, so far as the writer is aware, there is nothing in the present paper especially original with himself, except possibly one or two of the combinations of formulæ, and the only reason that can be urged for supposing originality in even that direction is the fact that such combinations have never fallen under his observation. The object of the paper therefore, is to partially systematize our knowledge of this important subject, at the same time putting that knowledge in a form for convenient use. Such systematization is necessarily crude owing to the undeveloped condition of the subject.

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